(Non-SUSY) Yang-Mills/QCD on $R^2 \times T^2$, Adiabatic continuity, and η' potential

Yuya Tanizaki (Yukawa Institute, Kyoto)

Based on : 2201.06166 (with Mithat Ünsal (NCSU)), 2402.04320, 2405.12402 (with Yui Hayashi (YITP)), 2505.07467 (with both)

Study 4d gauge theories on $\mathbb{R}^2 \times \underbrace{T^2}_{\text{'t Hooft twist}}$

- Part 1 : Pure SU(N) YM
  - Reliable semiclassics on small T^2 ($NL \lesssim \Lambda^{-1}$).
  - Center vortex = Fractional instanton w/ $Q_{top} = 1/N$.
    = KvBLLY Monopole instantons
  - Area law of W(C), N-branch structure of θ-vacua
- Part 2 : QCD w/ fundamental quarks.
  - Derivation of chiral Lagrangian including η'
  - Witten - Veneziano - like η' - mass formula.
  - $\eta' \sim \eta' + 2\pi N$ instead of $\eta' \sim \eta' + 2\pi$.

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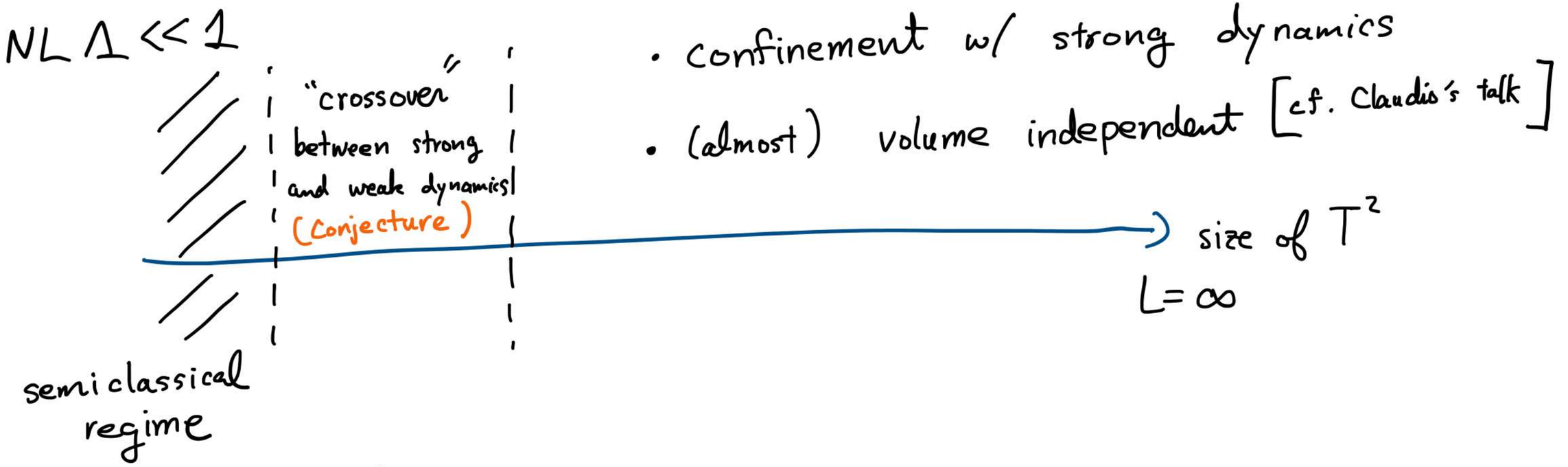
Semiclassical regime for 4d YM on $\mathbb{R}^2 \times T^2$ w/ 't Hooft flux

$$L\Lambda \sim O(1)$$



- confinement w/ strong dynamics
- (almost) volume independent [cf. Claudio's talk]

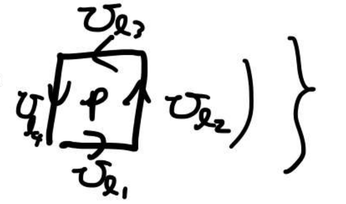
Claim (YT, Ünsal, '22)

We can prove confinement for $NL\Lambda \ll 1$ using the semiclassical method.

$\mathbb{Z}_N$ 1-form center symmetry & θ-periodicity anomaly

$SU(N)$ link variable; $\mathbb{Z}_N$ plaquette variable; (Background : $dB = 0$)

$$S_{\text{Wilson}}[U_\ell, B_p] = \beta \sum_p \mathrm{Re}\left\{ \mathrm{tr}\left(1 - e^{-\frac{2\pi i}{N} B_p} U_{\ell_3} U_{\ell_4} U_{\ell_2} U_{\ell_1}\right)\right\}$$



B : $\mathbb{Z}_N$-valued 2-form gauge field for center symmetry = 't Hooft flux/twist

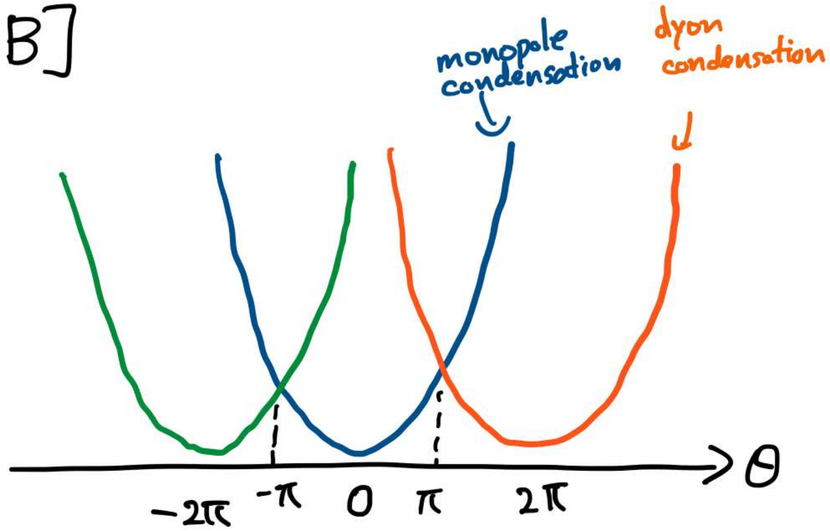
$$\begin{cases} B_p \mapsto B_p + (d\lambda)_p \\ U_\ell \mapsto e^{\frac{2\pi i}{N}\lambda_\ell} U_\ell \end{cases}$$

← gauged center transformation

With the presence of B, θ-periodicity is mildly violated by a contact term of B:

$$Z_{\theta+2\pi}[B] = e^{\frac{2\pi i}{N}\int \frac{1}{2} B \cup B} Z_\theta[B]$$

[Gaiotto, Kapustin, Komargodski, Seiberg 2017
(cf. van Baal '82)
(purely lattice derivation:
Abe, Morikawa, Onoda, Suzuki, YT '23)]



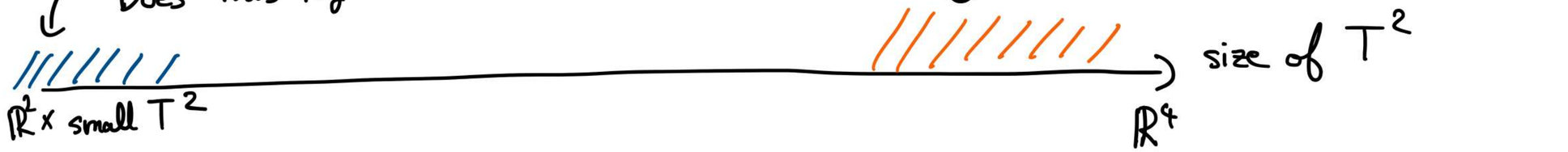
Semiclassical approach for confinement via T^2-compactification

Weakly coupled thanks to small T^2

↓ Does this regime show confinement?

confinement of our interest

↓ But, strongly coupled & difficult.



2d Symmetry

- $\mathbb{Z}_N^{(1)}$: center sym. for 2d Wilson loop
- $\mathbb{Z}_N^{(0)} \times \mathbb{Z}_N^{(0)}$: "conventional" center symmetry for Polyakov loops P_3 & P_4.

T^2-compact. ⟸

4d Symmetry

$\mathbb{Z}_N^{(1)}$ in 4d

& $p = \int_{T^2} B \in \mathbb{Z}_N$: 't Hooft flux.

2d Anomaly

$$Z_{\theta+2\pi}[B_{2d}] = e^{i\frac{2\pi}{N}p\int B_{2d}} Z_\theta[B_{2d}]$$

⟸

4d Anomaly

$$Z_{\theta+2\pi}[B] = e^{\frac{2\pi i}{N}\int \frac{1}{2}B\cup B} Z_\theta[B]$$

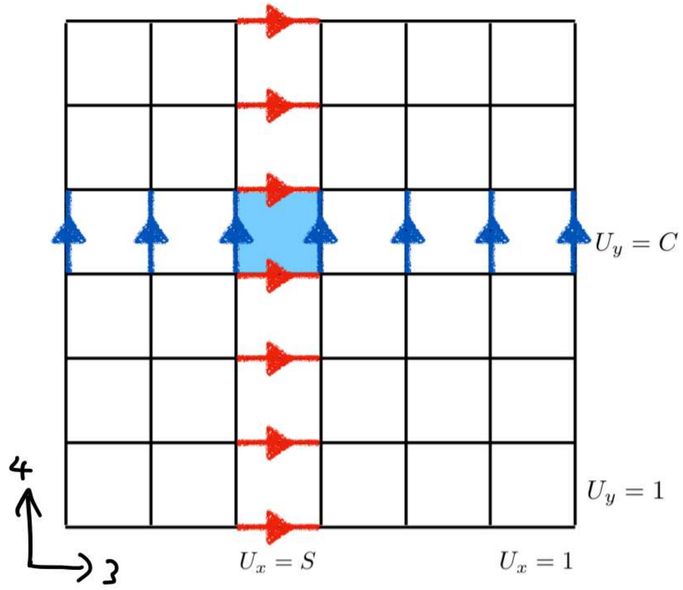
Activation of 't Hooft flux p w/ $\gcd(N,p)=1$ preserves 4d anomaly maximally.

't Hooft flux & Classical vacuum

Lattice action

$$S_W[U_\ell, B] = -\frac{1}{g^2}\sum_P \left(e^{-iB_P}\,\mathrm{tr}[U_P] + e^{iB_P}\,\mathrm{tr}[U_P^\dagger] \right).$$

$$B_P = \begin{cases} \frac{2\pi}{N} & \text{(for the plaquette indicated with light blue)} \\ 0 & \text{(otherwise)} \end{cases}$$



We can minimize this action by setting

$$U_\ell = \begin{cases} S = \begin{pmatrix} 0 & & \\ & \ddots & \\ & & 0 \end{pmatrix} \\ C = \begin{pmatrix} 1 & & \\ & \ddots & \\ & & \omega^{N-1} \end{pmatrix} \\ \mathbb{1} \end{cases}$$

[* Any classical minimum is gauge equivalent to this one]

$$\Rightarrow \quad P_3 = S \,, \quad P_4 = C \,.$$

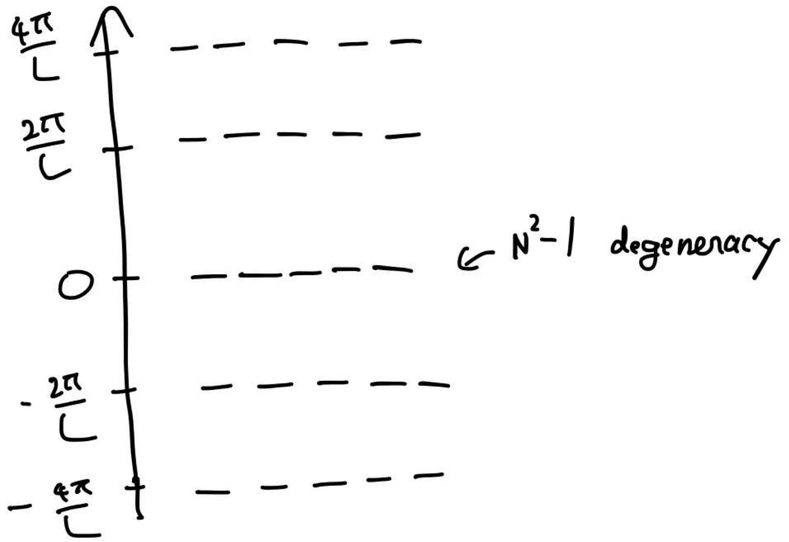
This configuration completely preserves $\mathbb{Z}_N^{[0]} \times \mathbb{Z}_N^{[0]}$.

Perturbative spectrum

Put 4d YM on $\mathbb{R}^2 \times T^2$.

Perturbative spectrum of 2d gauge fields on $\mathbb{R}^2$ part:

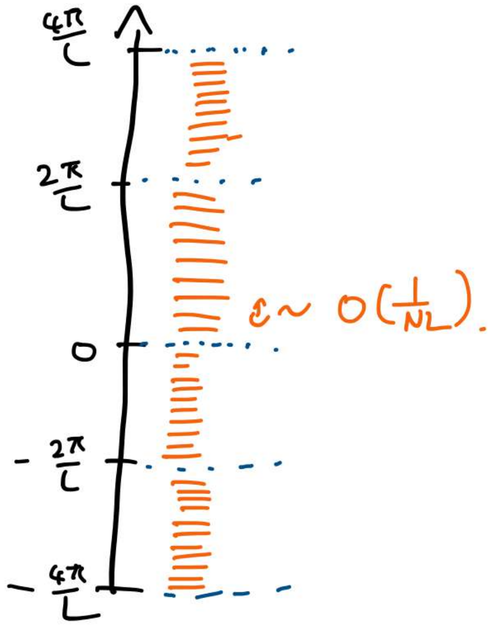
Without twist



$$M_{KK}^2 = \left(\frac{2\pi}{L}\right)^2 (l_3^2 + l_4^2)$$

- There exist zero modes.

With twist



$$M_{KK} = \left(\frac{2\pi}{L}\right)^2 \left(\left(l_3 + \frac{p_3}{N}\right)^2 + \left(l_4 + \frac{p_4}{N}\right)^2 \right)$$

for the color basis $e^{-\frac{2\pi i}{N}\frac{p_3 p_4}{2}} C^{-p_3} S^{p_4}$.

- No zero modes.
- Gap $\sim \frac{2\pi}{NL}$.

2d $\mathbb{Z}_N^{(1)}$ symmetry & center vortex

- For 2d effective theory,

$P_3 = S$ and $P_4 = C$ behave as Adjoint Higgs with orthogonal VEV:

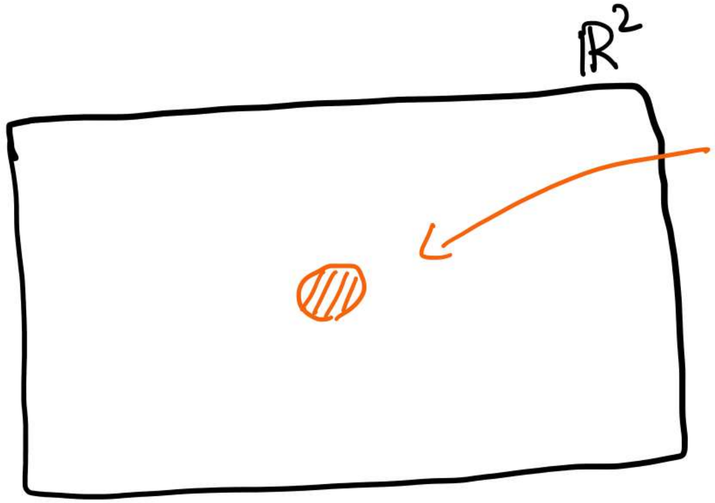
$$SU(N) \xrightarrow{\text{Higgs}} \mathbb{Z}_N.$$

$\Rightarrow$ 2d 1-form symmetry is spontaneously broken at classical vacua.

- Broken discrete symmetry $\Rightarrow$ Degenerate ground state

$\Rightarrow$ Topological solitons connecting them

(Domain walls for 0-form symmetry)

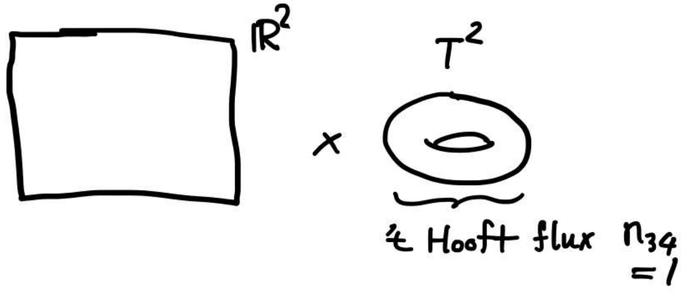


Soliton = Center vortex

Center vortex = fractional instanton on $\mathbb{R}^2 \times T^2$

In this setup, the minimal topological charge is given by

$$Q_{top} = \frac{1}{8\pi^2}\int \mathrm{tr}(F\wedge F) = \frac{1}{N}$$



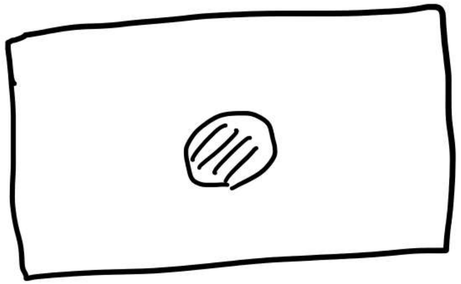
(More precisely, $Q_{top} \in \frac{1}{N}\left(\frac{-\epsilon_{\mu\nu\rho\sigma} n_{\mu\nu} n_{\rho\sigma}}{8}\right) + \mathbb{Z}$ (van Baal '82))

If there exists a self-dual configuration, its Yang-Mills action becomes

$$S_{YM} = \frac{8\pi^2}{g^2}|Q_{top}| = \frac{8\pi^2}{g^2 \cdot N}$$

Gonzalez-Arroyo, Montero '98, Montero '99 numerically confirmed such a classical solution exists:

center vortex
or fractional instanton.



$$\left(\begin{array}{l} Q_{top} = \frac{1}{N} \\ S_{YM} = \frac{8\pi^2}{g^2 N} \end{array}\right)$$

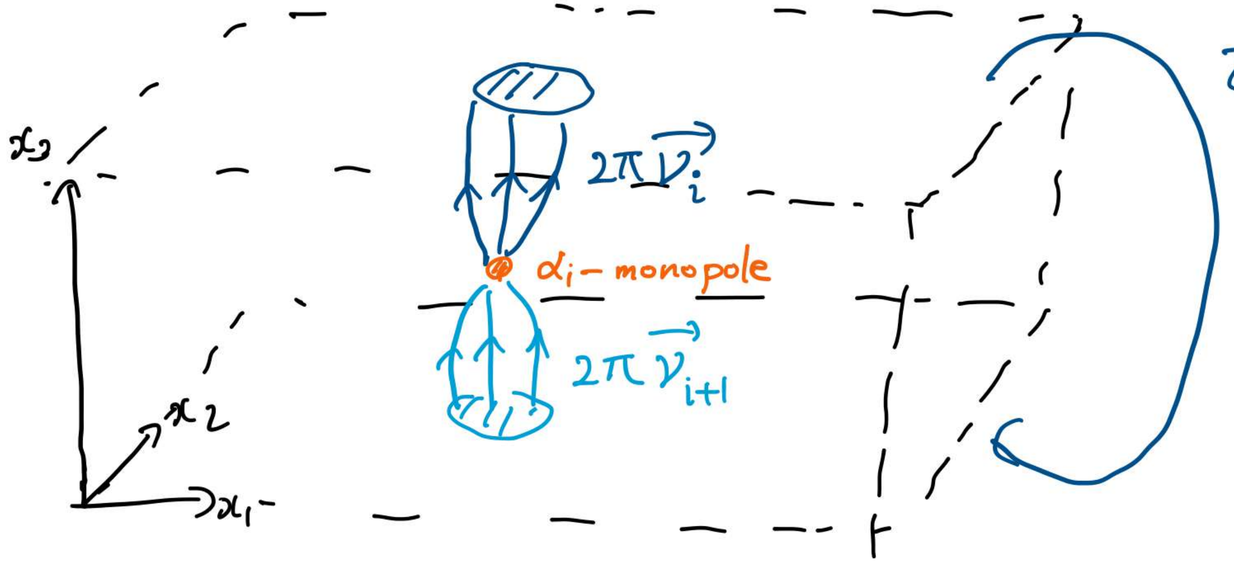
(cf. Garcia Perez, Gonzalez-Arroyo, '92,⋯, Itou '18, Wandler '24)

Center vortex on $\mathbb{R}^2 \times \underbrace{T^2}_{\text{flux}}$ = KuBLLY monopole instanton

$SU(N)$ gauge field on $\mathbb{R}^3 \times S^1$ w/ nontrivial holonomy : N fundamental monopoles (Lee, Yi '97; Lee, Lu '98; Kraan, van Baal '98)

[$\Rightarrow$ 3d semiclassics by Ünsal, ... since 2007]

α_i – monopole emits the magnetic flux $2\pi\alpha_i = 2\pi(\nu_i - \nu_{i+1})$.



$\mathbb{Z}_N$-twisted b.c. (= 't Hooft flux on T^2)

$2\pi\nu_i \longmapsto 2\pi\nu_{i+1}$

[Hayashi, YT 2405.12402]

$\mathbb{Z}_N$-twisted b.c. gives the perturbative gap $\frac{2\pi}{NL_3}$ $\Rightarrow$ Magnetic flux localizes.

Monopole = Junction of the center vortex

(cf. Ambjorn, Giedt, Greensite '99, de Forcrand, Pepe '00)

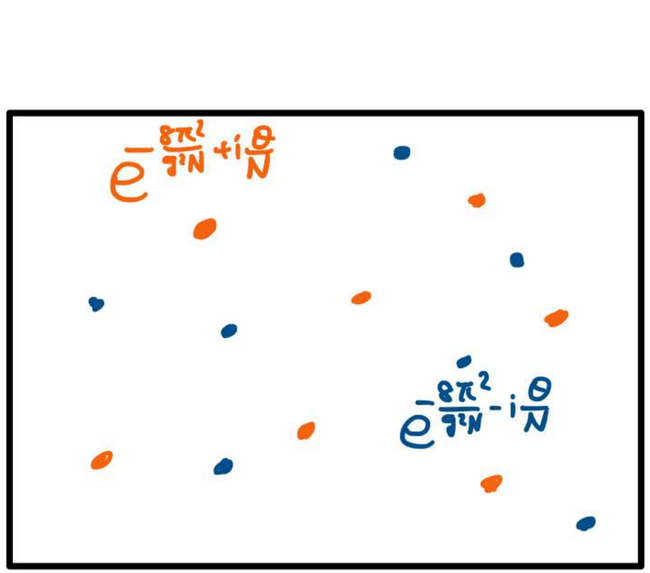
Dilute gas approximation

2d gluon fields are perturbatively gapped by 't Hooft twist.

$\Rightarrow$ Center vortex, or fractional instanton, does NOT have the size moduli.

$\Rightarrow$ Dilute gas approximation is available.

(* In 4d pure YM, DIGA is invalidated because of IR divergences.)



n : # of vortices

$\bar{n}$: # of anti-vortices

$$Q_{top} = \frac{n-\bar{n}}{N}.$$

Partition funcion on $M_2 \times T^2$ & θ-dependence

$M_2 \to \mathbb{R}^2$

To make the computation well-defined, we compactify $\mathbb{R}^2$ to some closed 2-manifold M_2.

Using the 1-loop vertex of the center vortex

$$K \cdot e^{-\frac{8\pi^2}{g^2 N} + i\frac{\theta}{N}},$$

we have

$$Z(\theta) = \sum_{n,\bar{n}\geq 0} \frac{\delta_{n-\bar{n}\in N\mathbb{Z}}}{n!\,\bar{n}!} \left(V \cdot K e^{-\frac{8\pi^2}{g^2 N} + i\frac{\theta}{N}}\right)^n \left(V \cdot K e^{-\frac{8\pi^2}{g^2 N} - i\frac{\theta}{N}}\right)^{\bar{n}}$$

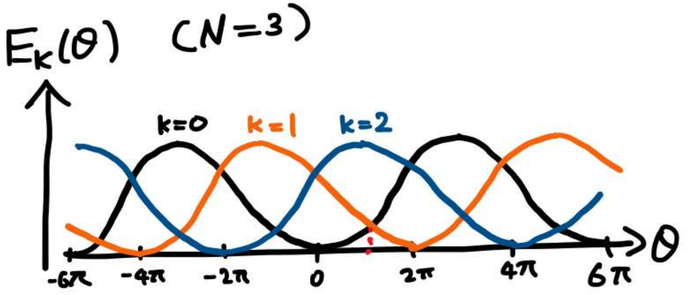
(vortex: $e^{-\frac{8\pi^2}{g^2 N} + i\frac{\theta}{N}}$; anti-vortex: $e^{-\frac{8\pi^2}{g^2 N} - i\frac{\theta}{N}}$)

$$= \sum_{k=0}^{N-1} \exp\left[-V\left(-2K e^{-\frac{8\pi^2}{g^2 N}} \cos\left(\frac{\theta - 2\pi k}{N}\right)\right)\right]$$

$E_k(\theta)$: Ground-state energy densities

$\Rightarrow$

- N-branch structure of ground states.
- Each branch has a fractional θ-dependence.



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$$\sum_{k=0}^{N-1} e^{\frac{2\pi i}{N} k(n-\bar{n})} = \delta_{n-\bar{n} \in N\mathbb{Z}}$$

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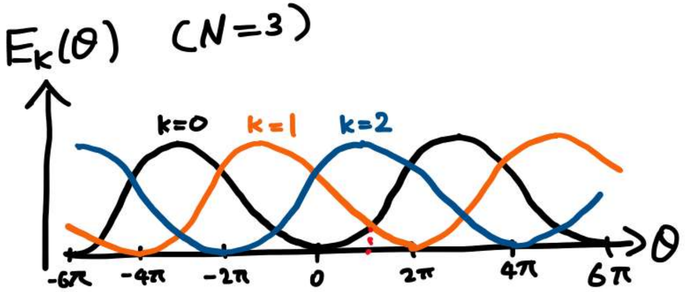


Physical Meaning of the branch label $k \in \mathbb{Z}_N$

① Distinction as Symmetry-Protected Topological (SPT) states

When 4d $\mathbb{Z}_N^{(1)}$ is unbroken,

$$Z[B] \overset{\text{low energy}}{\sim} \exp\left(i \int \frac{N k}{4\pi} B \wedge B\right).$$

[cf. Gaiotto, Kapustin, Komargodski, Seiberg '17]

② Distinction based on Wilson-'t Hooft classification ['t Hooft '78-'81]

't Hooft ('79): Area law for $W(C)$ is not enough to classify confinement states.
Use also $H(C,\Sigma)$.

Screened line operators are generated by $H(C,\Sigma) \cdot W^k(C)$.

(ex $SU(2)$)

	$W(C)$	$H(C,\Sigma)$	$W(C)H(C,\Sigma)$
Higgs	Perimeter	Area	Area
Confinement $\theta \sim 0$	Area	Perimeter	Area
Confinement $\theta \sim 2\pi$	Area	Area	Perimeter.

[Equivalence ① $\Leftrightarrow$ ② : Nguyen, YT, Ünsal 2306.02485]

Adiabatic continuity conjecture

smoothly connected ?

$NL\Lambda \lesssim 1$

- Weakly-coupled
- Many expected features of 4d dynamics are obtained

$L\Lambda \sim O(1)$

- Confinement w/ strongly-coupled dynamics
- Difficult to solve

(cf.
T^4 : twisted Eguchi-Kawai model (Gonzalez-Arroyo, Okawa '83, '10, ...)
$\mathbb{R} \times T^3$: van Baal '80s, Garcia-Perez, Gonzalez-Arroya ... '90s, Yamazaki, Yonekura '17, Cox, Poppitz, Wandler '21
$\mathbb{R}^3 \times S^1$: Davies, Hollowood, Khoze '99, Ünsal, Yaffe, Shifman, Poppitz, ... ~'07)

Claim

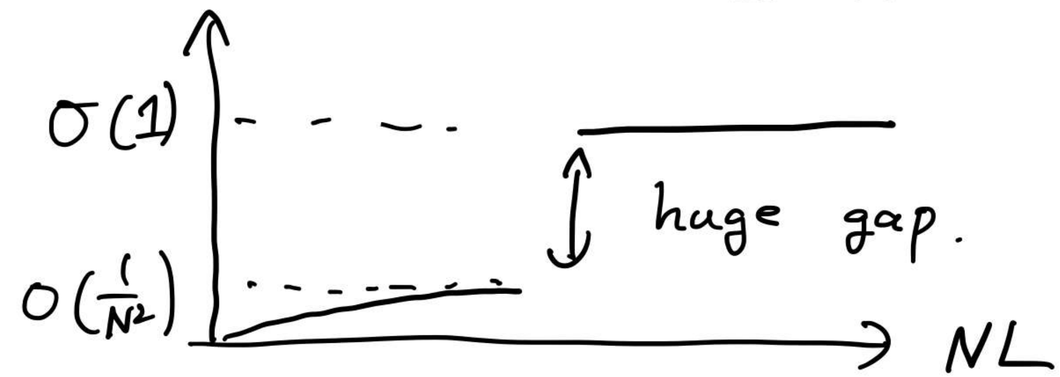
Suitable choice of (N, P) achieves the continuity for pure YM w/ $N \gg 1$.

Evidence for $N = 2$ ⇒ Bergner, Gonzalez-Arroyo, Solar 2505.10396

Large-N $(\mathbb{Z}_N^{(1)})_{2d}$ breaking for $p=1$

If $p=1$, dilute gas approximation of center-vortices gives

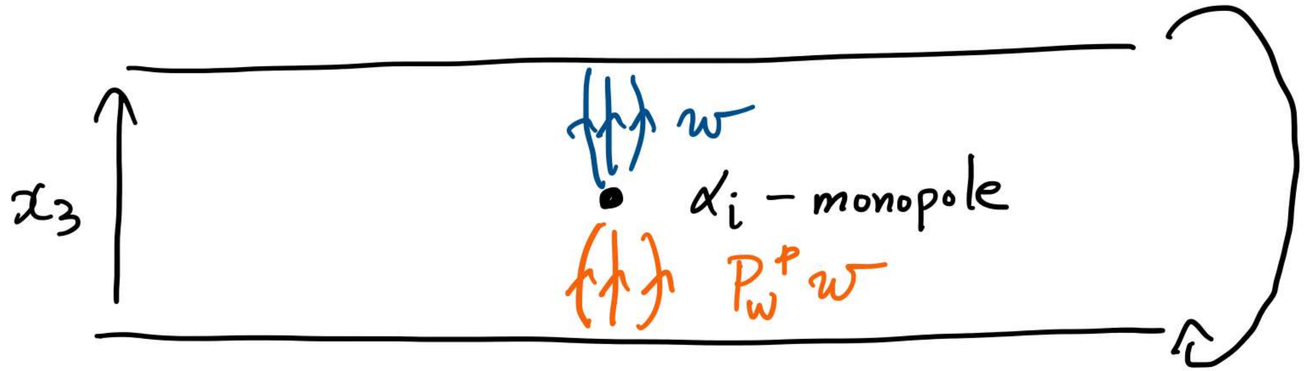
$$\sigma_{\text{fund}} \sim \Lambda^2 \cdot \underbrace{(NL\Lambda)^{\frac{5}{3}}}_{O(1) \text{ for semiclassics}} \cdot \underbrace{\sin^2\left(\frac{\pi}{N}\right)}_{\to 0 \text{ as } N\to\infty}$$



$\Rightarrow$ For suitable p, how can we close this gap.

Center-vortex fractional instanton for general (N,P)

Magnetic flux $\vec{w}$ of self-dual center vortex must satisfy



't Hooft twist:

$$\vec{\nu}_i \mapsto \vec{\nu}_{i+P} = P_w^P \vec{\nu}_i$$

$$\vec{w} = \vec{\nu}_i + \vec{\nu}_{i+P} + \cdots + \vec{\nu}_{i+(q-1)P}$$

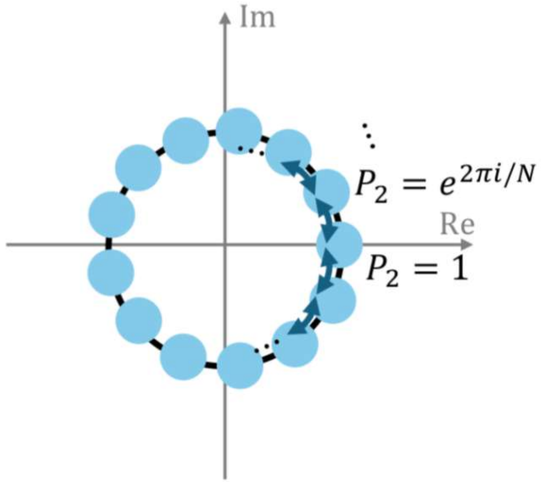
with $q \in \mathbb{Z}_N$ s.t. $q \cdot P = 1 \mod N$

$$-) \; P_w^P \vec{w} = \vec{\nu}_{i+P} + \cdots + \vec{\nu}_{i+(q-1)P} + \vec{\nu}_{i+Pq} \qquad (\vec{\nu}_{i+1})$$

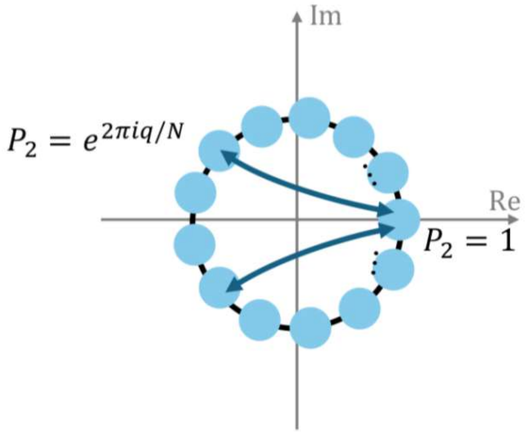
$$\vec{w} - P_w^P \vec{w} = \vec{\nu}_i - \vec{\nu}_{i+1} \; (= \vec{\alpha}_i)$$

$\Rightarrow$ $\frac{1}{N}$-fractional instanton carries $\frac{q}{N}$-flux.

Dilute gap approximation of $\frac{8}{N}$-flux center-vortex instantons



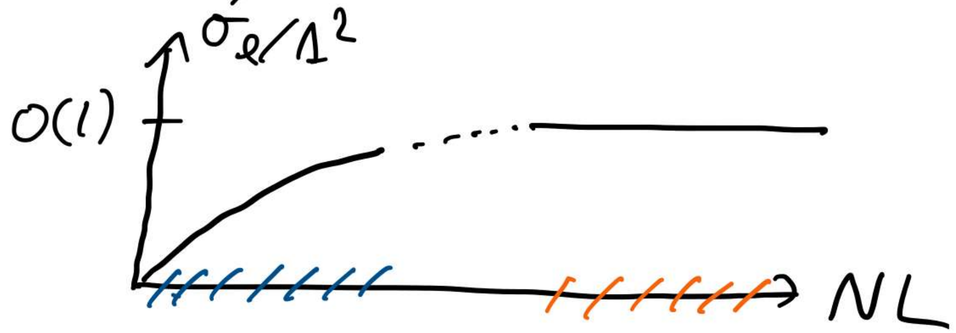
(a) Large N with $p = q = 1$



(b) Large N with $q \sim O(N)$

$$\Rightarrow \sigma_{\ell\text{-string}} \sim \Lambda^2 \underbrace{(NL\Lambda)^{\frac{5}{3}}}_{O(1)} \cdot \sin^2\left(\underbrace{\frac{\pi 8}{N}}_{O(1)} \ell\right)$$

For $\ell \sim O(1)$,



Continuity is now reasonable!

Study 4d gauge theories on $\mathbb{R}^2 \times \underbrace{T^2}_{\text{'t Hooft twist}}$

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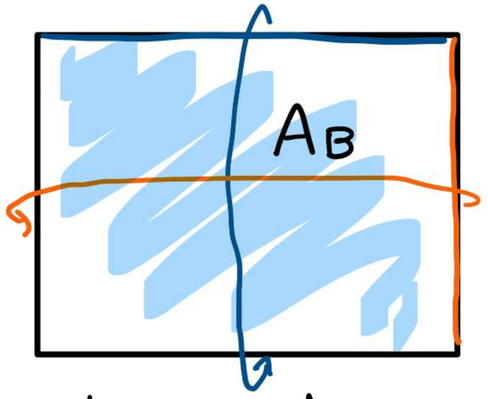
- Part 2 : QCD w/ fundamental quarks.
  - Derivation of chiral Lagrangian including η'
  - Witten - Veneziano - like η' - mass formula.
  - $\eta' \sim \eta' + 2\pi N$ instead of $\eta' \sim \eta' + 2\pi$.

$U(1)_B$ monopole flux & 't Hooft flux on T^2

Fundamental quarks explicitly violates $\mathbb{Z}_N^{(1)}$ $\Rightarrow$ No 't Hooft B.C., naively.

Use $U(1)_B = \frac{U(1)_q}{\mathbb{Z}_N}$ monopole flux.



Cocycle condition

$$\begin{cases} \psi(L, x_4) = g_3^\dagger(x_4)\, e^{-i\frac{\phi_3(x_4)}{N}}\, \psi(0, x_4) \\ \psi(x_3, L) = \underbrace{g_4^\dagger(x_3)}_{\text{color-transition functions}}\, \underbrace{e^{-i\frac{\phi_4(x_3)}{N}}}_{U(1)_q\text{-transition functions}}\, \psi(x_3, 0) \end{cases}$$

$$g_3^\dagger(L)\, g_4^\dagger(0)\, e^{-i\frac{1}{N}(\phi_3(L)+\phi_4(0))} = g_4^\dagger(L)\, g_3^\dagger(0)\, e^{-i\frac{1}{N}(\phi_4(L)+\phi_3(0))}.$$

$U(1)_B = U(1)_q/\mathbb{Z}_N$ monopole flux

$$2\pi = \int_{T^2} dA_B = (\phi_3(L) - \phi_3(0)) - (\phi_4(L) - \phi_4(0))$$

$$\Rightarrow \quad g_3^\dagger(L)\, g_4^\dagger(0) = g_4^\dagger(L)\, g_3^\dagger(0)\, \boxed{e^{\frac{2\pi i}{N}}}$$

't Hooft flux !!

2d Effective Lagrangian on $\mathbb{R}^2 \times T^2$ w/ baryon - 't Hooft flux

4d QCD $\overset{\text{classical \& Perturbative}}{\Longrightarrow}$
- Gauge : Gapped gluons & Center vortices
- Quark : 2d Dirac fermion as 4d Dirac zero modes w/ $\int_{T^2} dA_B = 2\pi$.

$\Downarrow$ Bosonization & Semiclassical Analysis

U : 2d $U(N_f)$-valued field (π, K, η & η') [YT, Ünsal 2201.06166; Hayashi, YT 2402.02430]

$$\mathcal{L}_{\text{2d effective}} = \frac{1}{8\pi} \mathrm{tr}(\partial_\mu U^\dagger \partial_\mu U) - \mathrm{tr}[MU + \text{c.c.}]$$
$$+ i \frac{1}{12\pi} \mathrm{tr}[(U^\dagger dU)^3]$$
$$- e^{-\frac{8\pi^2}{g^2 N}} \left(e^{-\frac{i\theta}{N}} (\det U)^{1/N} + \text{c.c.} \right)$$

[$\Leftarrow$ If we neglect massive η' part, this is consistent w/ 4d chiral Lagrangian on $\mathbb{R}^2 \times T^2$ w/ $\int_{T^2} dA_B = 2\pi$.]

Revisiting $U(1)_A$ problem

$U(1)_A$: η' (i.e. $e^{i\eta'} = \det U$) is too massive according to SSB of the chiral symmetry $SU(N_f)_L \times SU(N_f)_R \times U(1)_V \times U(1)_A$.

$\Rightarrow$ $U(1)_A$ is not a symmetry of quantum theory !

η' gets the mass even if $M_{quark} = 0$.

Previous proposals

- Kobayashi - Maskawa - 't Hooft : $-\cos(\eta' - \theta)$
- Witten - Veneziano's large $-N$: $\eta'^2 + O\left(\frac{\eta'^4}{N^2}\right)$

2d center - vortex theory : $-\cos\left(\frac{\eta' - \theta}{N}\right)$

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$\frac{1}{N}$ fractionalize

large-N

2d center-vortex theory : $-\cos\left(\frac{\eta' - \theta}{N}\right)$

How does $\frac{1}{N}$ appear? What is its fermionic picture?

't Hooft [cf. Thamas's talk @ finite-T]

$\mathbb{R}^2 \times T^2$
w/ 't Hooft flux
$\Longrightarrow$

$$e^{-\frac{8\pi^2}{g^2}} \cdot e^{-i\theta} \det U(x)$$

4d instanton = N independant
center vortices

$$\prod_{i=1}^{N} e^{-\frac{8\pi^2}{g^2 N}} e^{-i\frac{\theta}{N}} \left(\det U(x_i)\right)^{1/N}$$

each term behaves almost independently

Periodicity of η'

Recall that we introduced η' by

$$e^{i\eta'} = \det U.$$

$\Rightarrow \eta' \sim \eta' + 2\pi$, which does not fit $-\cos\left(\frac{\eta'-\theta}{N}\right)$.

[Same problem occurs for the Witten–Veneziano formula]

Solution Reinstate the YM confinement vacua labelled by $k \sim k+N$.

$$-e^{-\frac{8\pi^2}{g^2N}}\cos\left(\frac{\eta'-\theta}{N}\right) \Longrightarrow -e^{-\frac{8\pi^2}{g^2N}}\cos\left(\frac{\eta'-\theta+2\pi k}{N}\right).$$

The correct periodicity for η' involves the shift of k : (Hayashi, YT 2402.04320)

$$(\eta'+2\pi, k) \sim (\eta', k+1).$$

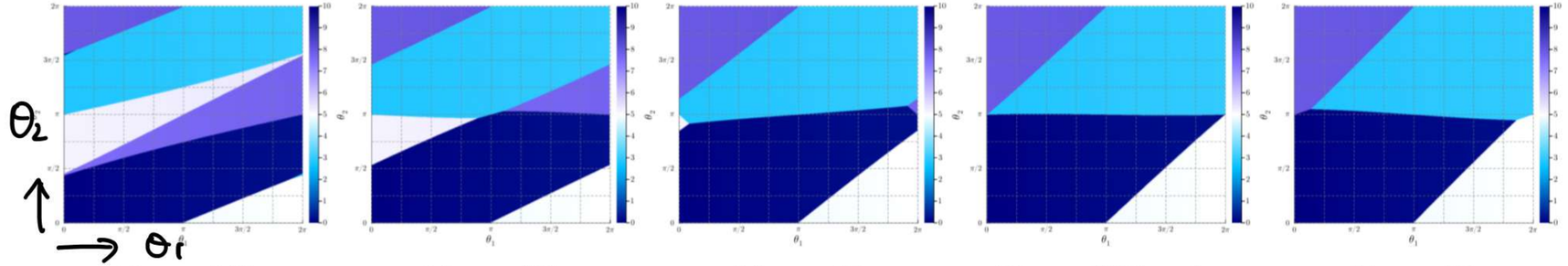
$\Rightarrow \eta' \sim \eta' + 2\pi N$ by "eating" the k index.

Application to QCD-like theories

- QCD (Anti-Sym / Sym) [YT, Ünsal 2205.11339]

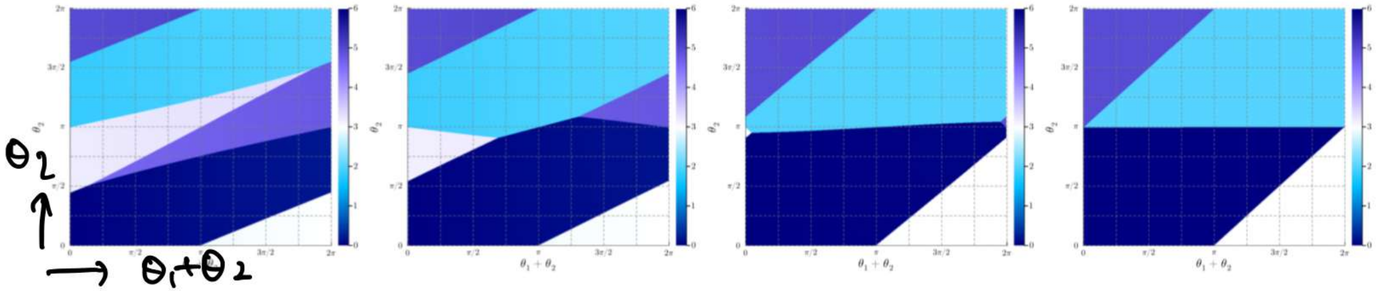
  Fractional instanton always has $Q_{top} = \frac{1}{N}$, but the fermion zero-mode fractionalizes as $e^{i\left(\frac{N\mp 2}{N}\eta' - \frac{\theta}{N}\right)}$ $\Rightarrow$ $N\mp 2$ chiral-broken vacua.

- Karasik-Komargodski non-SUSY duality cascade for QCD (Bi-Fund).
  [Y. Hayashi, YT, H. Watanabe 2404.16803]
  [A. Karasik, Z. Komargodski 1904.09551]



(a) $m\mu = 0.02$ (b) $m\mu = 0.06$ (c) $m\mu = 0.2$ (d) $m\mu = 0.263 \approx m^*\mu$ (e) $m\mu = 0.3$

SU(2)×SU(5) QCD(BF)



(f) $m'\mu \approx 0.02182$ (g) $m'\mu = 0.08$ (h) $m'\mu = 1.2$ (i) $m'\mu = 100$

SU(2) × SU(3) QCD(BF)

Summary

Studying 4d gauge theories on $\mathbb{R}^2 \times T^2$ w/ 't Hooft flux is useful to investigate some aspects of confinement.

- Center vortex can be used for analytically well-controlled semiclassics.
- Center vortex in this setup $=$ $\frac{1}{N}$ fractional instanton
  $=$ KvBLL monopole instanton
- Fresh perspective on $U(1)_A$ & η'.
  - $\frac{1}{N}$ fractionalization of Kobayashi-Maskawa-'t Hooft vertex
  - η' is correlated w/ N-branch YM vacua : $(\eta'+2\pi, k) \sim (\eta', k+1)$.
- Other fermions (QCD(Sym/ASym/BF)) can also be studied. (YT, Ünsal '22; Hayashi, YT, Watanabe '23, '24)

  ⇒ Large-N orbifold equivalence.